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Regression Equations for Estimating Stature From Long Bones of Early Holocene European Samples

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ABSTRACT Regression equations for estimating living stature from long bone lengths have been calibrated on a sample of European Neolithic skeletons (33 males and 27 females) by using both least-squares (model I) and major-axis (model II) regression techniques. Stature estimates of the skeletal sample have been made by means of Fully's anatomical method, a procedure based on the sum of all osseous components of height, providing the best approximations to the actual stature. The calculated equations have been tested, along with those generally used to predict stature of earlier European remains, on a small, well-preserved sample including Late Upper Paleolithic, Mesolithic, and Neolithic skeletons. The results indicate that the model II equations are particularly useful when very short or very tall individuals are involved and, at the same time, are among the best predictors of stature in less extreme conditions. © 1996 Wiley-Liss, Inc.

Beginning with Pearson's work (1899), regression equations have been a commonly used tool in studying biometrical relationships between stature and main limb bone lengths. Least-squares regression techniques applied to samples in which stature was measured during life or after death have provided the basis for deriving different sets of equations calibrated on different population samples. Developments in physical and forensic anthropological research have resulted in alternative approaches involving both new analytic procedures and new types of data. In particular, persuasive arguments have been made that regressions utilizing the major axis of the correlation plane are more adequate than least-squares linear regressions in predicting the stature of very short or very tall specimens (Olivier, 1976; Feldesman and Lundy, 1988; Jungers, 1988). Moreover, in the past few years, some authors have derived equations from skeletal samples (Lundy and Feldesman, 1987; Sciulli et al., 1990; Sciulli and Giesen, 1993) of which the stature was calculated by means of Fully's (1956) anatomical method. The anatomical method, based on the sum of all the skeletal components of height, results in the best approximation to the actual stature (Olivier, 1960; Breul, 1974; El Najjar and McWilliams, 1978; Stewart, 1979; Rösing, 1988), and a few forensic cases reported by Lundy (1988) point to a very high level of reliability. This procedure is worthy of attention because it permits the calibration of equations from past population samples.

Converting long-bone lengths to stature evaluations provides important information both for qualifying a skeletal population from the physical point of view and for paleoanthropological studies dealing with body size variation and its links to ecological and biocultural variables. Clearly, the reconstruction of the stature of ancient remains

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TABLE 1. *Descriptive statistics (mean and standard deviation) of the Neolithic sample*[1]

	Cranial height	Vertebral column	Bicondylar femur	Condylo-malleolar tibia (Broca)	Foot height	Anatomical stature
33 males	14.09 ± 0.50	53.24 ± 2.08	43.51 ± 2.56	36.02 ± 2.33	5.97 ± 0.27	163.63 ± 6.17
27 females	13.15 ± 0.39	49.11 ± 1.69	39.71 ± 1.97	32.63 ± 1.86	5.21 ± 0.24	150.61 ± 4.93

	Maximum length humerus	Maximum length radius	Maximum length femur	Condylo-malleolar tibia (Martin 1)	Bicondylar femur + condylo-malleolar tibia
33 males	31.03 ± 1.67	24.13 ± 1.53	43.74 ± 2.56	35.90 ± 2.33	79.41 ± 4.79
27 females	28.26 ± 1.49	21.48 ± 1.48	40.06 ± 1.98	32.51 ± 1.86	72.22 ± 3.76

[1] Measurements in centimeters.

by means of specific equations, rather than with those derived from modern populations characterized by different body proportions, should result in an improvement of the accuracy of the estimates.

Both these alternative approaches will be taken into account here. Data on stature (dependent variable) and long-bone lengths (independent variable) have been drawn from European Neolithic skeletons, and equations have been derived using both major-axis (model II) and least-squares (model I) regression techniques (Sokal and Rohlf, 1981). The latter equations have been calculated in spite of some theoretical reservations, providing a means of comparison for a full evaluation of the results arising from model II.

MATERIAL AND METHODS

The sample used for deriving regression equations includes 60 well-preserved Neolithic skeletons (33 males and 27 females) from different European countries. The material provided the basis for a previous work (Formicola, 1993), in which information about geographic distribution of the samples, technical aspects for stature evaluation, and measurement definitions can be found.

The wide distribution in time and space of the Neolithic material undoubtedly implies some biological differentiation among the population samples. However, this differentiation does not seem to greatly affect the variability of height and its components. It can be noted (Table 1) that the standard deviations are low and comparable to those found by Sciulli and coworkers (1990) in a small sample of prehistoric Ohio Native Americans used for deriving specific equations. Moreover, Sjovold's (1990) recent work suggests that stature itself is the most important determinant of body proportions, pointing to closer similarities among individuals belonging to the same stature class than among individuals belonging to the same geographic group.

Assuming also that sexual dimorphism in trunk/limb ratio results mainly from differences in stature, Sjovold (1990) pools male and female samples for deriving model II regression equations. Pooling males and females yields a larger sample and results in a wider distribution of stature values. Since the error of the estimates is greatest at the extremes of the range, the resulting equations are less reliable for both tall males and short females. Moreover, while it is generally accepted that males and females differ in body proportions, it is not clear that all such differences depend solely on differences in height. For these reasons we preferred to keep separate male and female samples, developing sex-specific regression equations for estimating living stature from the humerus, radius, femur, tibia, and the combination of femur plus tibia.

The choice, among model II regression techniques, of the major axis instead of the reduced major axis was suggested by the tests performed on a small sample (see below), indicating a higher accuracy of the former procedure.

In order to check the efficacy of these equations we used a small, well-preserved skeletal sample, suitable to the application of the anatomical method, including Late Upper Paleolithic, Mesolithic, and three very short (<154 cm) and three very tall (>182 cm)

TABLE 2. Sample used for testing regression equations

Specimens	Stature	Period
Male		
Romanelli 1 (Italy)	172.2	Late Upper Paleolithic
Arene Candide 5 (Italy)	162.0	Late Upper Paleolithic
Sejro (Denmark)	159.0	Mesolithic
Loschbour (Luxemburg)	163.5	Mesolithic
Teviec 16 (France)	170.2	Mesolithic
Gramat (France)	168.8	Mesolithic
Rastel (France)	168.2	Mesolithic
Mondeval (Italy)	166.4	Mesolithic
Afalou-Bou-Rhummel 2 (Algeria)	177.1	Ibero-Maurusian
Ain Dokkara (Algeria)	163.2	Capsian
Barmaz II 19 (Switzerland)	153.4	Neolithic
Chamblandes 6 (Switzerland)	153.5	Neolithic
Vucedol 3/4 (Croatia)	150.1	Neolithic
Overvindinge 1 (Denmark)	191.4	Neolithic
Auzay 5 (France)	188.2	Neolithic
Most Ao 8400 (Czech Rep.)	182.8	Neolithic
Female		
Bad Dürrenberg (Germany)	155.7	Mesolithic
Teviec 1 (France)	154.3	Mesolithic
Teviec 6 (France)	151.6	Mesolithic
Bonifacio (France)	150.3	Mesolithic
Birsmatten (Switzerland)	150.4	Mesolithic

Neolithic males. These six Neolithic skeletons were excluded from the computation of equations for evaluating the possible improvements provided by the major axis regression technique in such extreme conditions. The test sample is listed in Table 2.

Comparative analysis of the results was carried out using individual anatomically reconstructed living stature (skeletal height + soft tissue correction) and evaluations derived from the femur and tibia separately, the bones showing the best correlations with height. Values reported in Table 4 represent the mean error, obtained by averaging the absolute differences resulting in each single case between anatomical stature and lower limb bones derived stature. Moreover, in order to show whether the equations overpredict or underpredict stature, the same differences have been averaged taking into account the signed values. Thus, Table 5 reports the mean signed difference and the standard deviation as an indication of the magnitude of the errors.

The results are tabulated together with those provided by equations (Pearson, 1899; Breitinger, 1938; Bach, 1965; Olivier et al., 1978; Trotter and Gleser, 1952, 1977, for Whites and for Negroes) generally adopted to predict stature of earlier European remains.

REGRESSION EQUATIONS

The resulting equations (Table 3) show very high correlations and low standard errors of the estimates. Moreover, they confirm that the femur and tibia, alone or summed, are the most suitable bones for estimating stature both in males and females.

The application of these equations to the selected Neolithic sample (Table 4) bears evidence that model II equations lead to lower degrees of error both for short and for tall individuals. Moreover, it can be noted that for these subjects, model II equations are more reliable than equations traditionally adopted for estimating stature of prehistoric European remains. The only exception is represented by the Trotter and Gleser formulae for Whites, when applied to very tall individuals.

The application of model II regression equations to Late Upper Paleolithic and Mesolithic males provides good approximations, considering that deviations from the anatomical stature are of about 1.3 cm on average and with very few cases exceeding an error of 2 cm (Table 4). It is important to note that the sample is characterized by a medium height, ranging from 159–177 cm and that, in this case, a similar degree of error also results from our model I equations

TABLE 3. *Regression equations for estimation of living stature*[1]

	Least squares				Major axis	
Measures	Slope	Intercept	S.E.	r	Slope	Intercept
Males						
Humerus 1	3.31	60.87	2.77	0.90	4.04	38.05
Radius 1	3.65	75.57	2.63	0.91	4.38	57.90
Femur 1	2.23	65.90	2.37	0.93	2.55	52.08
Tibia 1	2.47	74.84	2.24	0.93	2.79	63.41
Femur 2 + tibia 1	1.22	66.66	1.99	0.95	1.30	60.42
Females						
Humerus 1	2.88	69.35	2.48	0.87	3.75	44.64
Radius 1	2.69	92.83	2.94	0.81	3.98	65.12
Femur 1	2.35	56.63	1.67	0.94	2.61	46.05
Tibia 1	2.46	70.57	1.85	0.93	2.80	59.58
Femur 2 + tibia 1	1.25	60.54	1.52	0.95	1.33	54.57

[1]Measurements are in centimeters. Humerus 1, radius 1, and femur 1 = maximum length; tibia 1 = condylo-malleolar length; femur 2 = bicondylar length.

TABLE 4. *Mean and range (centimeters) of the absolute individual differences in observed (anatomical method) and predicted stature*[1]

Males									
Samples	n	Stature	Major axis	Least squares	Pearson (1899)	Breitinger (1938)	Olivier et al. (1978)	Tr.Gl.W	Tr.Gl.N
Very short Neolithics	3	152.3 150.1–153.5	3.6 (0) 2.1–4.9	4.4 (0) 3.0–5.9	5.3 (0) 4.0–6.7	8.7 (0) 7.6–9.8	4.5 (0) 3.4–5.3	7.9 (0) 6.5–9.4	5.1 (0) 3.7–6.7
Very tall Neolithics	3	187.5 182.8–191.4	1.6 (2) 1.1–2.3	4.7 (0) 4.1–5.3	6.3 (0) 5.8–6.7	6.0 (0) 5.3–6.9	2.5 (1) 1.9–3.3	0.6 (3) 0.2–0.9	6.1 (0) 5.6–6.5
Late Upper Paleolithic and Mesolithics	10	167.1 159.0–177.1	1.3 (7) 0.5–3.6	1.5 (8) 0.0–3.9	1.7 (7) 0.1–4.3	2.5 (5) 0.7–5.7	1.3 (7) 0.1–3.0	3.0 (2) 0.1–5.8	1.7 (7) 0.0–4.4

Females									
Samples	n	Stature	Major axis	Least squares	Pearson (1899)	Bach (1965)	Olivier et al. (1978)	Tr.Gl.W	Tr.Gl.N
Mesolithics	5	152.5 150.3–155.7	0.3 (5) 0.1–0.7	0.3 (5) 0.3–0.4	0.5 (5) 0.2–0.7	4.7 (0) 3.1–5.6	3.6 (0) 2.5–4.1	4.2 (0) 4.0–4.5	1.2 (5) 0.6–1.4

[1]Parentheses indicate the number of cases falling within a ±2 cm margin of error. Tr. Gl.W. = Trotter and Gleser (1952) equations for Whites; Tr.Gl.N = Trotter and Gleser (1952) equations for Negroes.

and from the formulae of Olivier and coworkers (1978), Pearson (1899), and Trotter and Gleser (1952) (for Negroes).

Table 5 shows that evaluations derived from both equations follow the pattern exhibited by the other equations (Trotter and Gleser, 1952 for Whites excluded), overestimating statures of very short individuals and underestimating heights of very tall specimens. Looking at the middle-statured Late Upper Paleolithic and Mesolithic sample, it can be noted (Table 5) that the major-axis equations resort in slight underestimates (0.5 cm) and that greater underestimates result from our least-squares equations and from those of Olivier et al. (1978), Pearson (1899), and Trotter and Gleser (1952) for Negroes. On the contrary, the equations of Breitinger (1938), and particularly of Trotter and Gleser (1952) for Whites, result in overestimates.

In evaluating the results arising from the Trotter and Gleser equations (1952), it is important to note that Jantz and coworkers (1994) warn against a variant in the measurement of tibia length, which omits the malleolus. In order to test the efficacy of the suggested change, we have recalculated statures by adjusting the measurements of the tibia accordingly (i.e., by subtracting the 13.6 mm that these authors have found to be the mean difference between two lengths). The evaluations improve when short individuals are involved (Trotter and Gleser,

TABLE 5. Mean (centimeters) signed difference and standard deviation in observed (anatomical method) and predicted stature[1]

Samples	n	Major axis	Least squares	Pearson (1899)	Breitinger (1938)	Olivier et al. (1978)	Tr.G.W	Tr.Gl.N
Males								
Very short Neolithics	3	+3.6 ± 1.45	+4.4 ± 1.45	+5.3 ± 1.36	+8.7 ± 1.10	+4.5 ± 0.99	+7.9 ± 1.45	+5.1 ± 1.52
Very tall Neolithics	3	−1.6 ± 0.64	−4.7 ± 0.60	−6.3 ± 0.44	−6.0 ± 0.79	−2.5 ± 0.74	0.0 ± 0.36	−6.1 ± 0.45
Late Upper Paleolithic and Mesolithics	10	−0.5 ± 1.07	−0.9 ± 1.40	−0.9 ± 1.41	+1.6 ± 1.70	−0.7 ± 1.10	+3.0 ± 1.76	−1.0 ± 1.46
Females								
Samples	n	Major axis	Least squares	Pearson (1899)	Bach (1965)	Olivier et al. (1978)	Tr.Gl.W	Tr.Gl.N
Mesolithics	5	+0.3 ± 0.23	+0.2 ± 0.04	+0.3 ± 0.19	+4.7 ± 1.04	+3.6 ± 0.65	+4.2 ± 0.21	+1.2 ± 0.33

[1]A positive sign indicates an overestimate. Abbreviations as in Table 4.

1952 for Whites, +6.2, s.d. = 1.45; for Negroes, +3,6, s.d. = 1.52) but become less accurate in the case of tall specimens (for Whites, −1.7, s.d. = 0.82; for Negroes, −7.6, s.d. = 0.47). Taking into account the Late Upper Paleolithic and Mesolithic sample, a marked improvement of the results can be observed by using the Trotter and Gleser (1952) equations for Whites (+1.3, s.d. = 1.07), while those for Negroes result in higher errors (−2.5, s.d. = 1.92).

In conclusion, by using the length of the tibia without the malleolus, an improvement of the estimates can be observed when the Trotter and Gleser (1952) formulae for Whites are applied to short and medium-sized specimens, while those for Negroes improve the evaluations only in the case of low-statured specimens. It can be noted by comparing these data with those reported in Table 5 that the errors resulting from the new estimates remain systematically higher than those resulting from both the equations developed here.

Taking into account the female sample, the model II equations yield very accurate estimates (Tables 4 and 5), leading to errors of about 0.3 cm on average, a result also approached by the model I equations and by those of Pearson (1899) among the traditionally adopted formulae. A similar result can be obtained with the Trotter and Gleser (1952) equations for Negroes by adjusting the tibial length (−0.5, s.d. = 0.34), while the errors resulting from the formulae for Whites remain high (+2.2, s.d. = 0.21).

CONCLUDING REMARKS

The model II regression equations derived from Neolithic skeletons represent an alternative worthy of attention to equations commonly used to predict stature of earlier European populations. Comparative data reported in Tables 4 and 5 indicate that model II equations are useful when very short or very tall individuals are involved, and at the same time appear to be among the best predictors of stature for less extreme individuals. For this reason, in our opinion, the latter equations could prove particularly suitable in analyses focused on temporal or spatial stature variations and more in general when large variation in body size is foreseen among the samples studied.

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